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CP-Violation in the Decay $b \to s\gamma$ in the Left-Right Symmetric Model

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Abstract

The direct CP-violation in the left-right symmetric $SU(2) \times SU(2) \times U(1)$ model is investigated for the decay $b \to s\gamma$. The calculated CP-asymmetry for the wide range of parameters can be larger than in standard model and can have an opposite sign.

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The experimental and theoretical investigation of the decay $b \to s\gamma$ can give a sign for a new physics in the TeV region [1]. This decay has been extensively studied during the last years. The first experimental evidence was obtained at CLEO for the exclusive decay $\bar{B} \to K^{*}\gamma$ [2]. The decay $b \to s\gamma$ has been investigated theoretically for the standard model and its extensions [3]-[11]. CP-violation in $B-\bar{B}$ system was considered in [12].

In this paper we consider the CP asymmetry in the decay $b \to s\gamma$ for the left-right symmetric $SU(2) \times SU(2) \times U(1)$ model, which is one of the simplest extensions of the standard model. Calculated value of CP-asymmetry for some range of parameters of the model (the mass of the right W-boson, the ratio of two Higgs doublet vacuum expectation values, phases and mixing angles) is almost 2 times larger than in standard model and can have an opposite sign, while the decay rate is almost the same.

The Lagrangian of interaction of quarks with scalar and $SU(2) \times SU(2) \times U(1)$ gauge fields has the following form:

$$\begin{aligned} L = (A_{ik}\bar{\Psi}_{Li}\Phi\Psi_{Ri} + B_{ik}\bar{\Psi}_{Li}\tilde{\Phi}\Psi_{Ri} + c.c) + \\ ig_R\bar{\Psi}_{Ri}\hat{W}^a_R\sigma_a\Psi_{Ri} + ig_L\bar{\Psi}_{Li}\hat{W}^a_L\sigma_a\Psi_{Li} \end{aligned} \tag{1}$$

where i,k=1,2,3 and

$$\Phi = \begin{pmatrix} \eta^e & \xi^+ \\ \eta^- & -\xi^{o*} \end{pmatrix} \quad \tilde{\Phi} = \begin{pmatrix} \xi^o & \eta^+ \\ \xi^- & -\eta^{o*} \end{pmatrix} \quad \Psi_{i,L,R} = \begin{pmatrix} U \\ D \end{pmatrix}_{i,L,R}$$

The symmetry $SU(2) \times SU(2) \times U(1)$ can be broken to $SU(2)_L \times U(1)$ by means of vacuum expectation values (vev) of doublet or triplet fields [9, 10, 11]. As for $SU(2) \times U(1)$ symmetry breaking we assume that it takes place when the scalar field Φ acquires the vev:

$$\Phi = \begin{pmatrix} k & 0 \\ 0 & -e^{i\delta}k' \end{pmatrix}, \tag{2}$$

The interaction of quark charged current with W gauge boson and charged Higgs fields has the form:

$$\begin{aligned} L^{ch} &= \frac{1}{\sqrt{2}}(\bar{u},\bar{c},\bar{t})\Big[\hat{W_1}^+\left[-g_L\cos\beta K_L P_- - g_R\sin\beta e^{i\delta}K_R P_+\right] + \\ &+ \varphi^+\frac{g_L}{\sqrt{2}M_{W_L}}\Big[\Big(-\tan 2\theta K_L M_d + e^{i\delta}\frac{1}{\cos 2\theta}M_u K_R\Big)P_+ + \\ &+ \Big(\tan 2\theta M_u K_L - e^{i\delta}\frac{1}{\cos 2\theta}K_R M_d\Big)P_-\Big]\Big]\begin{pmatrix} d \\ s \\ b \end{pmatrix} \end{aligned} \tag{3}$$

where W_1 is the "light" (predominantly left-handed) charge gauge boson and β is the mixing angle between left and right W - bosons,

$$\tan 2\beta = 2\sin 2\theta\frac{g_R}{g_L}\frac{M^2_{W_L}}{M^2_{W_R}} \quad \tan\theta = -\frac{k'}{k}$$

K_L and K_R are Kobayashi-Maskawa mixing matrices for left and right charged currents respectively, $P\pm = (1 \pm \gamma_5)/2$,

$$M_u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}, \qquad M_d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

The matrices K_L and K_R can be expressed in such a form where K_L has only one complex phase and K_R has five complex phases [13]. In (3) we omit the term, connected with the interaction with heavy (predominantly right) W- boson, which is not relevant for $b \to s\gamma$ decay.

The effective lagrangian for $b \to s\gamma$ decay has the following form [9, 10, 11]:

$$\begin{aligned} H_{b\to s\gamma} &= -\frac{e}{16\pi^2}\frac{2G_F}{\sqrt{2}}m_b\Bigg(K^{L*}_{ts}K^L_{tb}A^{W_L}_{s\gamma}O^L_7 + e^{i\delta}K^{L*}_{ts}K^R_{tb}\beta\frac{m_t}{m_b^*}A^{W_{LR}}_{s\gamma}O^L_7 + \\ &+ e^{i\delta}K^{L*}_{ts}K^R_{tb}\frac{\sin 2\theta}{\cos^2 2\theta}\frac{m_t}{m_b^*}A^{\varphi^+}_{s\gamma}O^L_7 + \frac{m_s}{m_b}K^{L*}_{ts}K^L_{tb}A^{W_L}_{s\gamma}O^R_7 \\ &+ e^{-i\delta}K^{R*}_{ts}K^L_{tb}\beta\frac{m_t}{m_b^*}A^{W_{RL}}_{s\gamma}O^R_7 + e^{-i\delta}K^{R*}_{ts}K^L_{tb}\frac{\sin 2\theta}{\cos^2 2\theta}\frac{m_t}{m_b^*}A^{\varphi^+}_{s\gamma}O^R_7\Bigg) \end{aligned} \tag{4}$$

where

$$\begin{aligned} O^{L,R}_7 &= \bar{u}_s\sigma^{\mu\delta}(1\pm\gamma_5)u_bF_{\mu\nu}, \quad O^{L,R}_8 = \bar{u}_s\sigma^{\mu\delta}(1\pm\gamma_5)u_bG_{\mu\nu} \\ A^{W_L}_{s\gamma} &= \eta^{\frac{16}{23}}\left[\mathcal{A}^{W_L}_{s\gamma} + \frac{8}{3}\mathcal{A}^{W_L}_{sg}\left(\eta^{-\frac{2}{23}}-1\right) - \frac{232}{513}\left(\eta^{-\frac{19}{23}}-1\right)\right] \\ A^{W_{LR}}_{s\gamma} &= \eta^{\frac{16}{23}}\left[\mathcal{A}^{W_{LR}}_{s\gamma} + \frac{8}{3}\mathcal{A}^{W_{LR}}_{sg}\left(\eta^{-\frac{2}{23}}-1\right)\right] \\ A^{\varphi^+}_{s\gamma} &= \eta^{\frac{16}{23}}\left[\mathcal{A}^{\varphi^+}_{s\gamma} + \frac{8}{3}\mathcal{A}^{\varphi^+}_{sg}\left(\eta^{-\frac{2}{23}}-1\right)\right] \end{aligned} \tag{5}$$

where $\eta = \frac{\alpha_s(m_W)}{\alpha_s(m_b)}$ and the functions $\mathcal{A}^{W_L}_{s\gamma}$, $\mathcal{A}^{W_{L,R}}_{s\gamma}$, $\mathcal{A}^{\phi+}_{s\gamma}$ $\mathcal{A}^{W_L}_{sg}$, $\mathcal{A}^{W_{L,R}}_{sg}$, $\mathcal{A}^{\phi+}_{sg}$ was presented in [9, 10, 11, 14, 15, 16]:

$$\begin{aligned} \mathcal{A}^{W_L}_{s\gamma} &= Q_tF_1(x) + G_1(x), \quad \mathcal{A}^{W_L}_{sg} = F_1(x) \\ \mathcal{A}^{W_{L,R}}_{s\gamma} &= Q_tF_2(x) + G_2(x), \quad \mathcal{A}^{W_{L,R}}_{sg} = F_2(x) \\ \mathcal{A}^{\phi+}_{s\gamma} &= Q_tF_3(y) + G_3(y), \quad \mathcal{A}^{\phi+}_{sg} = F_3(y) \end{aligned} \tag{6}$$

and

$$\begin{aligned} F_1(x) &= -\frac{1}{(1-x)^4}\left[\frac{x^4}{4} - \frac{3}{2}x^3 + \frac{3}{4}x^2 + \frac{x}{2} + \frac{3}{2}x^2\log(x)\right] \\ G_1(x) &= -\frac{1}{(1-x)^4}\left[\frac{x^4}{2} + \frac{3}{4}x^3 - \frac{3}{2}x^2 + \frac{x}{4} - \frac{3}{2}x^3\log(x)\right] \\ F_2(x) &= -\frac{1}{(1-x)^3}\left[-\frac{x^3}{2} - \frac{3}{2}x + 2 + 3x\log(x)\right] \\ G_2(x) &= -\frac{1}{(1-x)^3}\left[-\frac{x^3}{2} + 6x^2 - \frac{15}{2}x + 2 - 3x^2\log(x)\right] \end{aligned} \tag{7}$$

$$F_3(y) = -\frac{1}{(1-y)^3}\left[-\frac{y^3}{2} + 2y^2 - \frac{3}{2}y - y\log(y)\right]$$
$$G_3(y) = -\frac{1}{(1-y)^3}\left[-\frac{y^3}{2} + \frac{1}{2}y + y^2\log(y)\right]$$
where $Q_t = 2/3$ is the electric charge of the top quark, $x = m_t^2/m_W^2$, $y = m_t^2/m_{\varphi^+}^2$. The direct CP- asymmetry for $b \to s\gamma$ decay arises only when one take into account the final state interaction effects, when the absorptive parts arise.

Absorptive parts of the decay amplitude arise from rescattering $b \to su\bar{u} \to s\gamma$, $b \to sc\bar{c} \to s\gamma$, $b \to sg \to s\gamma$:

$$\begin{aligned} H_{b\to s\gamma}^{absorbt} = i\frac{e}{16\pi^2}\frac{2G_F}{\sqrt{2}}m_b\Bigg\{&K_{ts}^{L*}K_{tb}^{L}A_{sg}^{W_L}O_8^L t_{sg\to s\gamma} + \sum_{q=u,c}K_{qs}^{L*}K_{qb}^{L}A_{sq\bar{q}}^{W_L}t_{sg\to s\gamma} + \\ &+e^{i\delta}K_{ts}^{L*}K_{tb}^{R}\beta\frac{m_t}{m_b^*}A_{sg}^{W_{RL}}O_8^L t_{sg\to s\gamma} + e^{i\delta}K_{ts}^{L*}K_{tb}^{R}\frac{\sin 2\theta}{\cos^2 2\theta}\frac{m_t}{m_b^*}A_{sg}^{\varphi^+}O_8^L t_{sg\to s\gamma} + \\ &+e^{-i\delta}K_{ts}^{R*}K_{tb}^{L}\beta\frac{m_t}{m_b^*}A_{sg}^{W_{RL}}O_8^R t_{sg\to s\gamma} + e^{-i\delta}\ K_{ts}^{R*}K_{tb}^{L}\frac{\sin 2\theta}{\cos^2 2\theta}\frac{m_t}{m_b^*}A_{sg}^{\varphi^+}O_8^R t_{sg\to s\gamma}\Bigg\} \end{aligned} \tag{8}$$

where
$$A_{sg}^{\varphi^+} = \eta^{\frac{14}{23}}\mathcal{A}_{sg}^{\varphi^+},\quad A_{sg}^{W_L} = \eta^{\frac{14}{23}}\left[\mathcal{A}_{sg}^{W_L} - 0.1687\right],\quad A_{sg}^{W_{LR}} = \eta^{\frac{14}{23}}\mathcal{A}_{sg}^{W_{LR}} \tag{9}$$
In the standard model only for the rescattering $b \to su\bar{u} \to s\gamma$ and $b \to sc\bar{c} \to s\gamma$ one obtains nonegligible contribution [14]. For the two Higgs doublet extension of the standard model or left-right symmetric model the rescattering $b \to sg \to s\gamma$ also must be taken into consideration. Taking into account the standard model result [14] we obtain the following result for the absorptive part of the decay $b \to s\gamma$ in left-right symmetric model:

$$\begin{aligned} H_{b\to s\gamma}^{absorbt} \simeq -i\frac{e}{16\pi^2}\frac{2G_F\alpha_s}{\sqrt{2}}m_b\{&O_7^L(\frac{2}{9}(K_{ts}^{L*}K_{tb}^{L}A_{sg}^{W_L} + e^{i\delta}K_{ts}^{L^*}K_{tb}^{L}\frac{K_{tb}^R}{K_{tb}^L}A_{sg}^R) + \\ &+\frac{1}{4}(K_{us}^{L^*}K_{ub}^{L} + 0.12K_{cs}^{L^*}K_{cb}^{L})c_1) + O_7^R\frac{2}{9}e^{-i\delta}K_{ts}^{L^*}K_{tb}^{L}\frac{K_{ts}^R}{K_{ts}^L}A_{sg}^R\} \end{aligned} \tag{10}$$

where
$$A_{sg}^R \equiv \beta\frac{m_t}{m_b^*}A_{sg}^{W_{LR}} + \frac{m_t}{m_b^*}\frac{\sin 2\theta}{\cos^2 2\theta}A_{sg}^{\varphi^+} \tag{11}$$
We note that our result is different from the one obtained in [15]: the contribution of the rescattering $b \to sg \to s\gamma$ differs from that in [15] by the factor 2/9. The CP-asymmetry for the decay $b \to s\gamma$ and $\bar{b} \to \bar{s}\gamma$ is defined as:
$$a_{cp} = \frac{\Gamma(\bar{b}\to\bar{s}\gamma) - \Gamma(b\to s\gamma)}{\Gamma(\bar{b}\to\bar{s}\gamma) + \Gamma(b\to s\gamma)} \tag{12}$$
The resulting CP-asymmetry is equal to:
$$\begin{aligned} a_{cp} = \frac{2\alpha_s}{(|C_7^L|^2 + |C_7^R|^2)v_t^* v_t}&\{(\mathrm{Im}v_t^* v_u + 0.12\mathrm{Im}v_t^* v_c)\times \\ &\times(A_{s\gamma}^{W_L} + H\cos\alpha A_{s\gamma}^R)\frac{c_1}{4} - (\mathrm{Re}v_t^* v_u + 0.12\mathrm{Re}v_t^* v_c)\times \\ &\times A_{s\gamma}^R H\sin\alpha\frac{c_1}{4} + \frac{2}{9}H\sin\alpha v_t^* v_t(A_{s\gamma}^{W_L}A_{sg}^R - A_{s\gamma}^R A_{sg}^{W_L})\Big\} \end{aligned} \tag{13}$$

where

$$
\begin{aligned}
&He^{i\alpha} \equiv e^{i\delta}\frac{K_{Rtb}}{K_{Ltb}}, \;\; A^R_{s\gamma} \equiv \beta\frac{m_t}{m_b^*}A^{W_{LR}}_{s\gamma} + \frac{m_t}{m_b^*}\frac{\sin 2\theta}{\cos^2 2\theta}A^{\varphi^+}_{s\gamma} \\
&v_t \equiv K^*_{Lts}K_{Ltb}, \qquad v_c \equiv K^*_{Lcs}K_{Lcb}, \qquad v_u \equiv K^*_{Lus}K_{Lub} \\
&C_7^L = A^{W_L}_{s\gamma} + \left(e^{i\delta}\frac{K^R_{tb}}{K^L_{tb}}\right)A^R_{s\gamma}, \quad C_7^R = e^{-i\delta}\frac{K^{R*}_{ts}}{K^{L*}_{ts}}A^R_{s\gamma}
\end{aligned}
\qquad (14)
$$

In the numerical results we take $\alpha_s = 0.24$, $c_1 \simeq 1.1$, $m_t = 175$GeV, $m_b = 4.5GeV$, $m_b^* \equiv m_b(m_t) = 3GeV$ [10]. The CP-asymmetry a_{cp} depends on the parameters of Kobayashi-Maskawa mixing matrix in Wolfensteins parametrization: λ=0.221, η, ρ [14, 17, 18, 19], and also it depends on the parameters of left-right symmetric model: α, $\tan 2\theta$, M_{W_R}, M_{φ^+}, H. We assume that $|H| = |K^R_{tb}/K^L_{tb}| \simeq 1$. For the fixed masses we vary the remaining parameters and obtain the allowed region of a_{cp} values. We take into account that in the left-right symmetric model the decay rate cannot differ sufficiently from those obtained in the standard model. The point is that the standard model predictions for decay rate are reasonable agreement with experiment. We present in Fig 1,2,3 the minimal and maximal values of the asymmetry for the various M_{W_R}, M_{φ^+} and $0 < \tan 2\theta < 3.5$ (the maximal and minimal values of a_{CP} are symmetric under changing of sign of $\tan 2\theta$). It is easy to see that the a_{CP} can be about 2 times larger than the maximal value of asymmetry in the standard model. For the masses of right sector $\geq$5TeV the asymmetry is rather sensitive on changes of the Higgs boson mass than the right W- boson mass. In contrary to the standard model, where the asymmetry have a negative sign, in our case the sign of the asymmetry can also be positive. The results for a_{CP} in Fig 1,2,3 are obtained under the assumption that the decay rate in left-right symmetric model can differ from the standard model predictions no more than $\Delta = 10\%$. Our calculations show that the results for maximal and minimal values of a_{CP} practically does not change when we vary Δ from 10% to 50%. This fact is illustrated in Fig 4, where we compare the results for Δ=10% and Δ=50% for masses $M_{W_R} = M_{\varphi^+}$=10TeV.

In table we present the a_{CP} minimal and maximal values in left-right symmetric model for some values of the parameters M_{W_R}, M_{φ^+}, $\tan 2\theta$ and for ρ, η "best fit" [19]: $(\rho, \eta) = (-0.05, 0.37)$. For $\eta = 0.37$ the standard model prediction for a_{CP} is -0.64%. For the same η the value of a_{CP} in left-right symmetric model can be almost 2.5 times larger.

In conclusion, we have calculated the CP asymmetry in the decay $b \to s\gamma$ for the left-right symmetric model $SU(2) \times SU(2) \times U(1)$. We have shown that the CP-asymmetry for the reasonable range of parameters can be larger than in standard model and can have an opposite sign.

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TABLE

	$\tan 2\theta$=1	$\tan 2\theta$=2	$\tan 2\theta$=3
M_{W_R}=1.5TeV, M_{φ^+}=10TeV	$(-1.51 \div 0.33)\%$	$(-0.76 \div 0.16)\%$	-
M_{W_R}=10TeV, M_{φ^+}=1.5TeV	-	-	-
M_{W_R}=10TeV, M_{φ^+}=10TeV	$(-0.90 \div -0.37)\%$	$(-1.27 \div 0.25)\%$	$(-0.39 \div 0.41)\%$
M_{W_R}=20TeV, M_{φ^+}=20TeV	$(-0.73 \div -0.55)\%$	$(-0.93 \div -0.35)\%$	$(-1.21 \div -0.06)\%$
M_{W_R}=50TeV, M_{φ^+}=10TeV	$(-0.93 \div -0.35)\%$	$(-1.31 \div 0.28)\%$	$(-0.48 \div 0.44)\%$
M_{W_R}=10TeV, M_{φ^+}=50TeV	$(-0.65 \div -0.63)\%$	$(-0.67 \div -0.61)\%$	$(-0.74 \div -0.54)\%$
M_{W_R}=50TeV, M_{φ^+}=50TeV	$(-0.66 \div -0.62)\%$	$(-0.70 \div -0.58)\%$	$(-0.77 \div -0.51)\%$

The minimal and maximal values of a_{CP} for ρ=-0.05, η=0.37 and some values of M_{W_R}, M_{φ^+} and $\tan 2\theta$.

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Figure Captions

Fig1. The maximal and minimal values of a_{CP} in % for M_{W_R}=5TeV, M_{φ^+}=5TeV (curves 1 and 2); for M_{W_R}=10TeV, M_{φ^+}=10TeV (curves 3 and 4); for M_{W_R}=20TeV, M_{φ^+}=20TeV (curves 5 and 6); for M_{W_R}=50TeV, M_{φ^+}=50TeV (curves 7 and 8).

Fig2. The maximal and minimal values of a_{CP} in % for M_{W_R}=1.5TeV and M_{φ^+}=10TeV (curves 1 and 2); M_{W_R}=5TeV and M_{φ^+}=10TeV (curves 3 and 4); M_{W_R}=10TeV and M_{φ^+}=10TeV (curves 5 and 6); M_{W_R}=20TeV and M_{φ^+}=10TeV (curves 7 and 8).

Fig3. The maximal and minimal values of a_{CP} in % for M_{W_R}=10TeV and M_{φ^+}=1.5TeV (curves 1 and 2); M_{W_R}=10TeV and M_{φ^+}=5TeV (curves 3 and 4); M_{W_R}=10TeV and M_{φ^+}=10TeV (curves 5 and 6); M_{W_R}=10TeV and M_{φ^+}=20TeV (curves 7 and 8).

Fig4. The maximal and minimal values of a_{CP} in % for M_{W_R}=10TeV, M_{φ^+}=10TeV and allowed difference from standard model 10% (curves 1 and 2);M_{W_R}=10TeV, M_{φ^+}=10TeV and allowed difference from standard model 50% (curves 3 and 4).

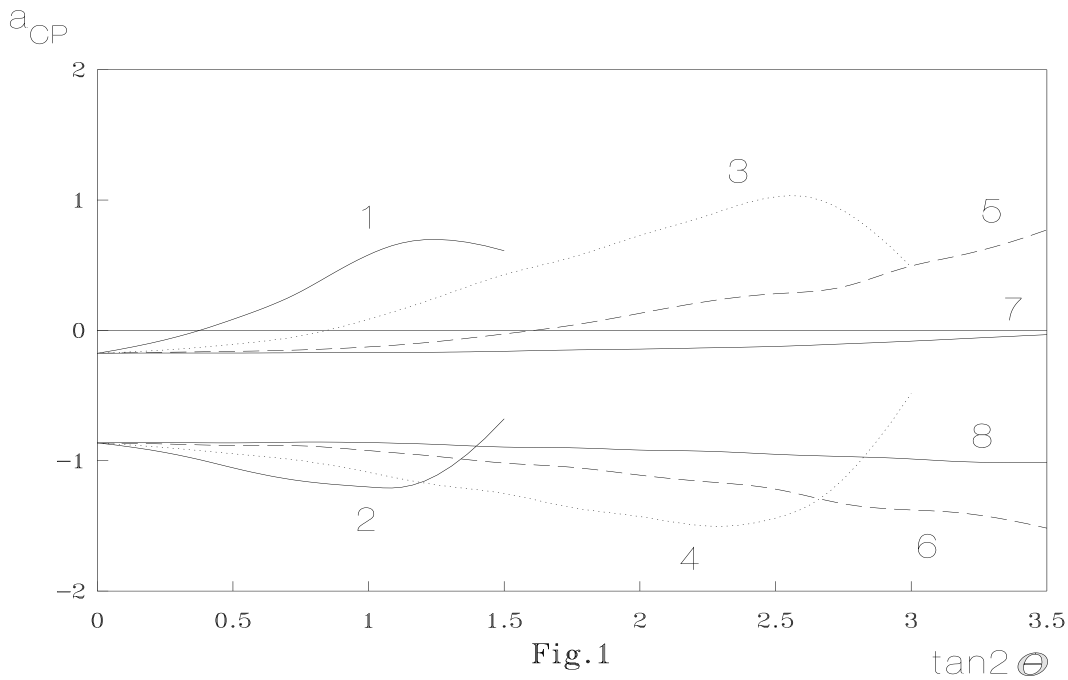
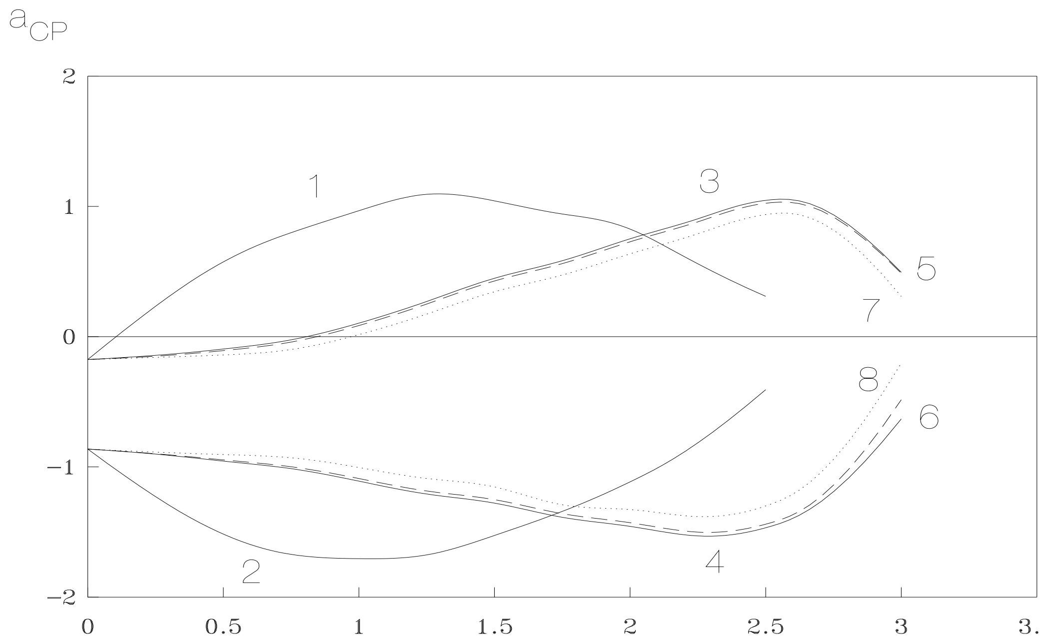
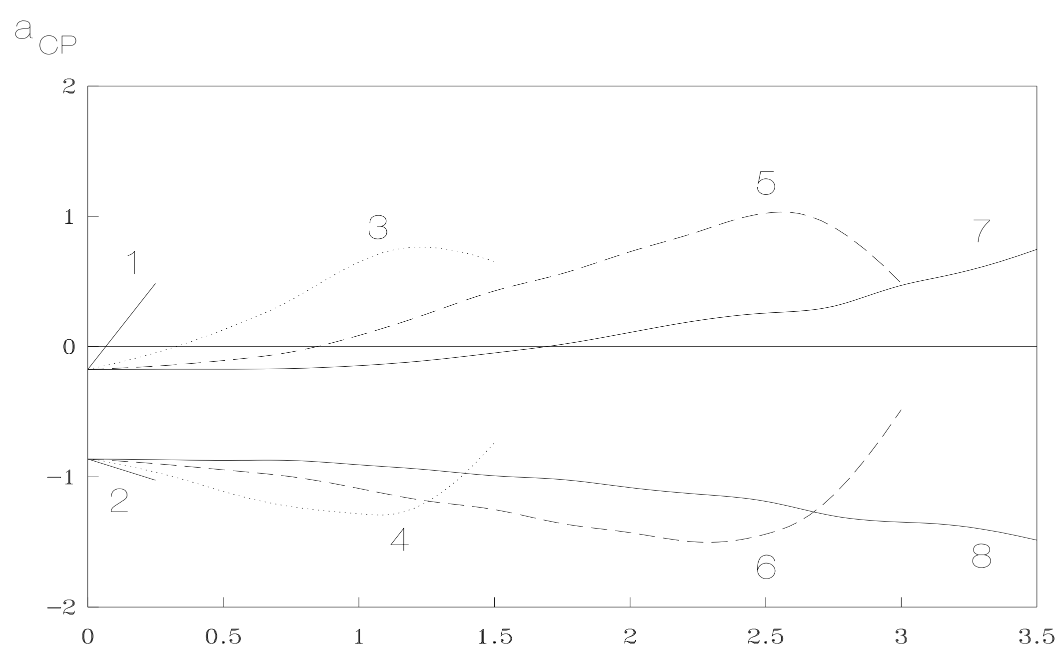


Fig.1



a_{CP}
2
1
0
−1
−2
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
5
6
7
8
tan2θ

Fig.2



a_{CP}
2
1
0
−1
−2
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
5
6
7
8
tan2θ

Fig.3

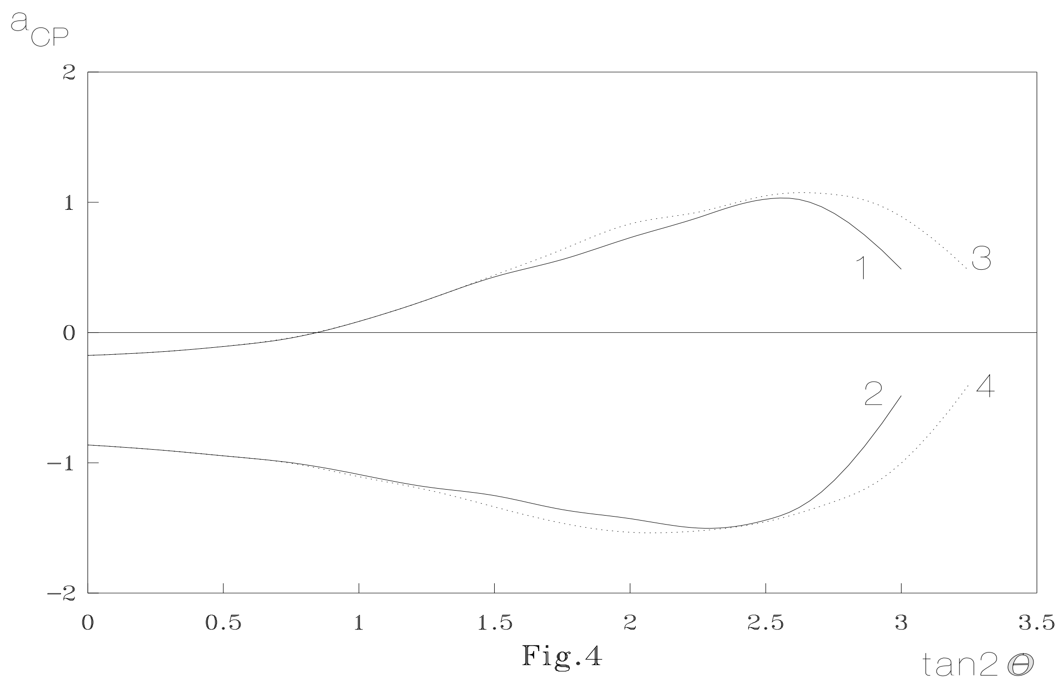


Fig.4